A DATA PROCESSING SYSTEM FOR THE ANALYSIS OF PROPELLER GENERATED FORCES AND MOMENTS IN SIX DEGREES OF FREEDOM

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by

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ABSTRACT

The design and operation of a special purpose digital signal processing system is explained. The system consists of a signal analyzer, an interface between the analyzer and the M.I.T. Compatible Time Sharing System, and appropriate computer programs. With inputs from an instrumented shaft in the M.I.T. variable-pressure propeller tunnel, the system permits rapid spectral analysis of propeller generated forces and moments in six degrees of freedom.

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Title: Professor of Naval Architecture

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1. INTRODUCTION

1.1 BACKGROUND. On July 1, 1968, the Department of Naval Architecture and Marine Engineering at M.I.T. submitted a proposal to the National Science Foundation to build a system that would permit unsteady hydrodynamic measurements in the variable-pressure water tunnel operated by the department (1). Research into means of reducing vibratory excitation to the hull of a ship depends upon the availability of methods to identify and measure periodic signals of known frequency, periodic signals of unknown frequency, and random signals. Of particular interest are the six components of periodic forces and moments on the propeller shaft due to non-uniform flow about the propeller and the fact that the propeller has a finite number of blades.

The design and construction of a specially instrumented shaft which will enable simultaneous measurement of the instantaneous values of the three forces and three moments due to the propeller interaction is covered in the Naval Engineer's thesis by Charles O. Horton (2). A matrix of miniature strain gauges and integrated circuit operational amplifiers built inside the shaft provides six signals in the 100 mv. to 1 volt range at an impedance of a few ohms. All the signals of interest will be below 1 khz. Each of the six forces and moments to be studied is a linear combination of these six signals, and the matrix of coefficients for this computation is to be determined by dynamic calibration of the shaft. A separate circuit in the shaft housing delivers a sharp synchronizing pulse once per revolution. Power to

the amplifiers and output signals from the amplifiers are transferred between the shaft and the outside via low noise slip rings.

The design of a simple digital data-processing system to rapidly analyze the signals received from the instrumented shaft is the subject of this report.

1.2 CHOICE OF SYSTEM. The principal requirement for the data-processing system were wide flexibility in types of analysis available to the experimenter, short turn-around time, and cost below $15,000.

Originally it was felt that all signal-processing equipment should be self-contained and located in the propeller tunnel experimental area. Complete signal-processing systems which could correlate, signal average, and spectrum analyze turned out to be too expensive. Considered next was a method of recording data from the experiment, converting it to digital form, and then punching it on paper tape or cards for submittal to the M.I.T. Information Processing Center for "batch" processing. The long turn-around time made this prospect discouraging. The final choice was to use a commercial digital signal analyzer in the experimental area, and to make an interface between the analyzer and the IBM 7094 computer used in the M.I.T. Compatible Time Sharing System (CTSS). The analyzer would collect data from the experiment, make the analog-to-digital conversion, and either store the data from a single sweep for analysis by an autocorrelating or crosscorrelating program in the 7094, or make hundreds of sweeps in averaging mode, leaving in its memory a digitized signal of enhanced

signal-to-noise ratio for use in a digital Fourier analysis.

The signal analyzer chosen was the Northern Scientific Model 550, with optional specifications as follows:

Memory:	1024 addresses; 10^5 counts per address
Number of inputs:	8 (With NS-305 eight input expander)
Readout:	Teletype Model 33ASRTC (includes tape punch and reader)

The NS-550 met the requirements of this project in the following specific ways:

1. Because it could read its output into a Teletype, which in turn can be connected to CTSS with a simple electrical interface to a Data-Phone, the computer interfacing problem would not be complicated.

2. The system, in the worst case, should resolve the third harmonic of a 9-bladed propeller operating at 2000 r.p.m. with all 8 inputs simultaneously. With time multiplexing of the eight inputs, this requires a sampling frequency of at least 14.4 khz., or a sampling period of no greater than 70 microseconds. The NS-550 can sample at intervals of 50 microseconds.

3. The total price of the analyzer and peripheral gear was about $12,000.

The electrical interface between the Teletype machine and the Data-Phone was designed and built by the author. It is electronically very simple and requires no attention or adjustment.

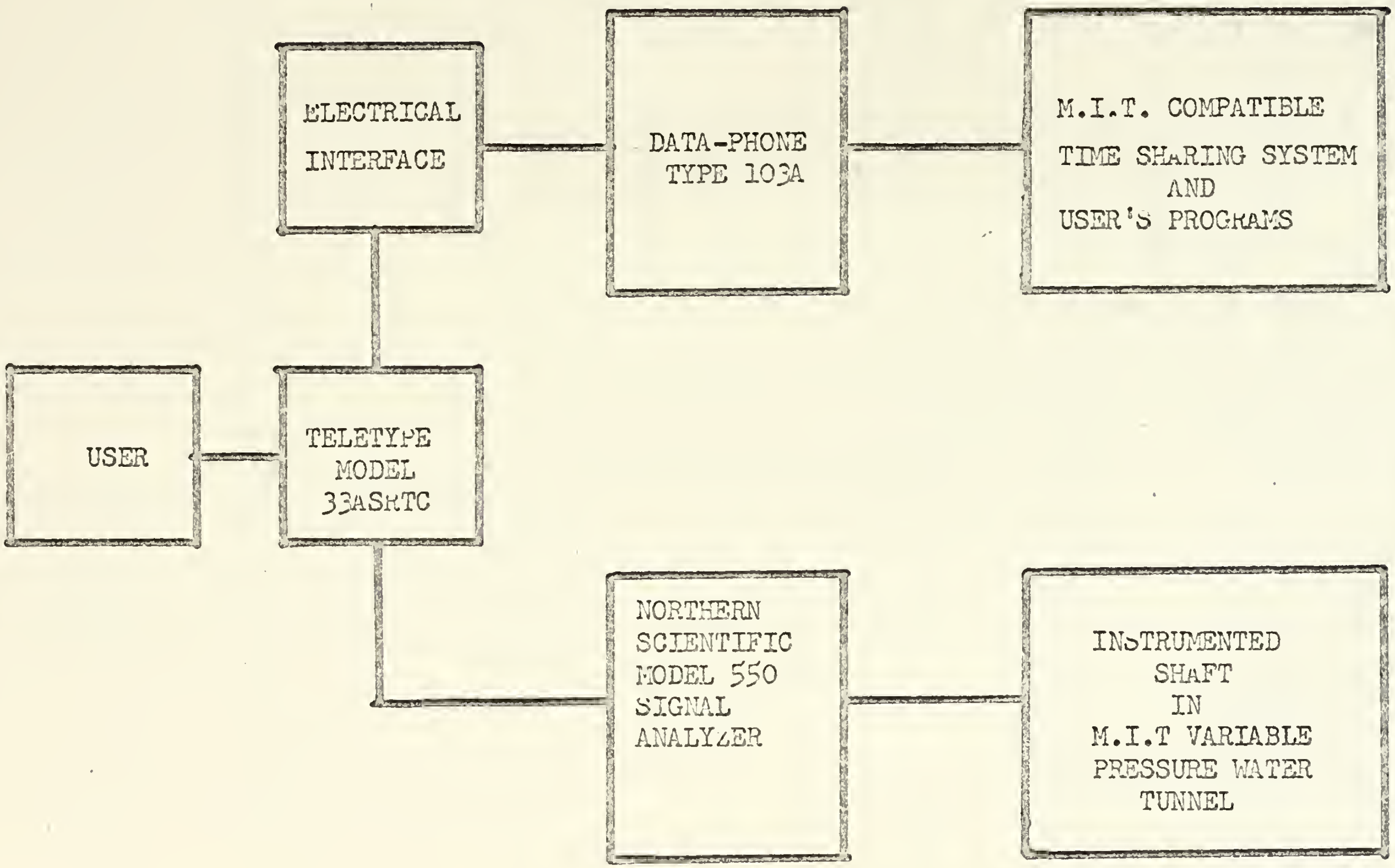


Fig. 1: Block Diagram of the Data Processing System

The system is completed by a conversational program written in Fortran IV which receives typed input from the experimenter and the signal analyzer and returns a Fourier analysis of each of the six forces and moments. For an analysis involving all 1024 memory locations in the analyzer, the turn-around time is about 20 minutes, most of which is analyzer read-out time. The program listing and documentation is given in Appendix A.

Fig. 1 is a block diagram of the completed signal analyzing system.

2. MODIFICATIONS TO EQUIPMENT

2.1 INPUT MODIFICATIONS. The NS-550 analyzer has an input impedance of at least 100K and switch-selected AC or DC coupling. The torque and thrust outputs from the shaft will have d.c. levels considerably higher than twice the a.c. signal components, and consequently the baseline adjustments on the analyzer will be insufficient to remove them. Unfortunately, the time constant of the a.c. coupling is .01 second, which is too small to pass low-frequency signals from the experiment without significant attenuation and phase shift.[1] This condition can be corrected by replacing the .1 μf. coupling capacitors in the eight input circuits with 10 μf. capacitors of equal voltage ratings.

2.2 SWEEP MODIFICATIONS. With 8 inputs and a memory cycle time of 50 microseconds, it takes .4 msec. to add one data point to each of the eight memory subdivisions. For simplicity, assume that each channel uses 125 memory locations. We desire to store data representing one complete propeller shaft revolution in each subdivision. The maximum period of one revolution is then 125 X .4 msec., which corresponds to a minimum shaft speed of 1200 r.p.m. Increasing the speed does nothing more than reduce the number of data points corresponding to one period.

Thus, for speeds of 1200 r.p.m. and above, the time base of the NS-550 must be set for .4 ms./point. Similarly, for speeds between 600 and 1200 r.p.m., a setting of .8 ms./point is required. However, as supplied by the manufacturer, the NS-550 skips over this range,

going from .2 ms./point to 2 ms./point.

The required modifications to the time base circuitry are not difficult, and circuit diagrams showing these changes can be obtained from Northern Scientific.[2]

2.3 LINE FEED MODIFICATIONS. Whenever CTSS is called up from a Teletype terminal, the computer begins by signaling the automatic answer-back device on the Teletype. The codes which are returned identify the particular Teletype machine and tell the computer if it must supply separate line feed signals whenever a carriage return is either sent or received. The two codes are identical except that in one a letter "C" appears in the two places which contain the letter "D" in the other code. If the answer-back device is set up for the "D" code, the computer supplies a separate line feed. If it is set up for the "C" code, the computer does not supply the separate line feed, but assumes that whenever a carriage return is either sent or received, the Teletype machine will line feed on its own.

The "D" code works satisfactorily for all input and output except for signal analyzer readout, because the signal analyzer produces a line feed of its own, and does not wait for the receipt of the computer-generated line feed before continuing. This causes confusion and loss of data.

Using the "C" code solves the above problem and introduces another: the operator must type his own carriage returns when typing

input to the computer, and must manually advance the paper for each successive line of data returned by the computer.

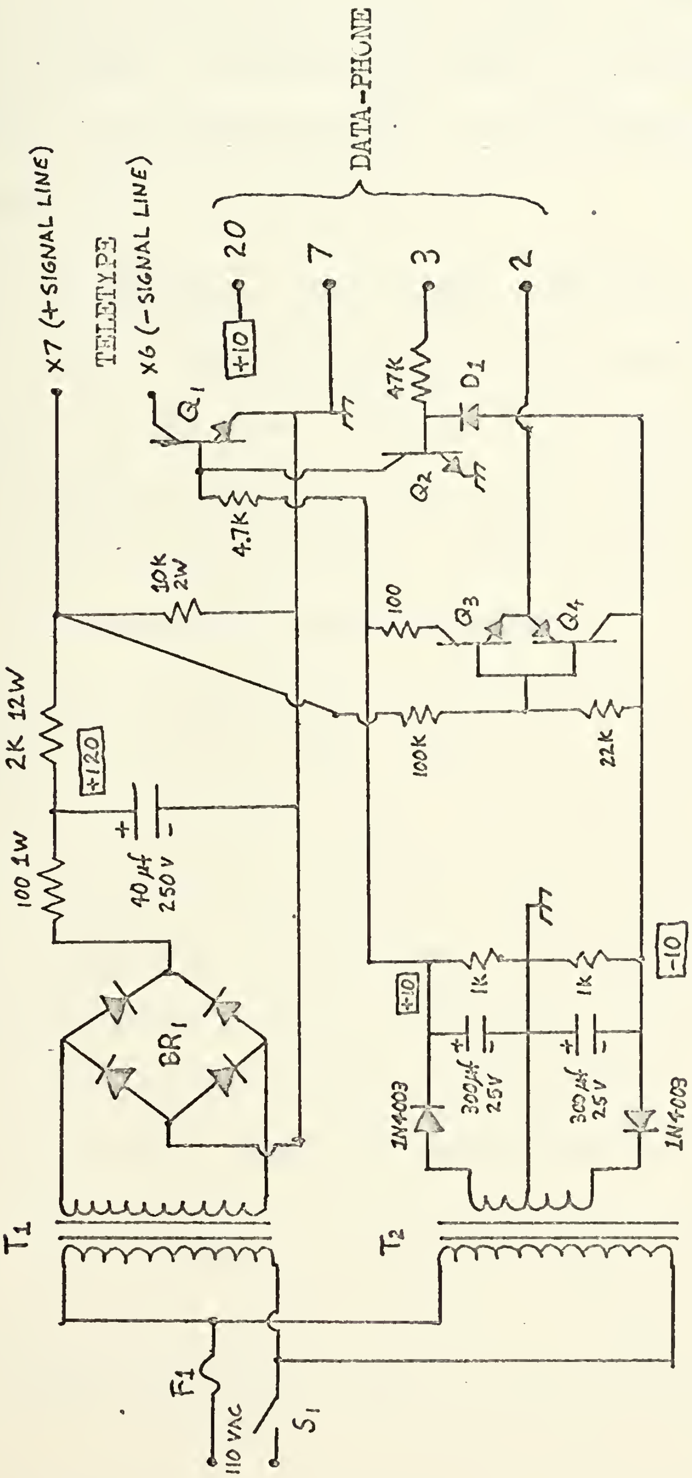
The solution to this problem is to set up the function box in the Teletype machine for "Suppress Line Feed" and "New Line, Line Feed," in accordance with the technical manual supplied with the machine (3). The "Suppress Line Feed" feature ignores all line feed signals received, and the "New Line, Line Feed" function automatically produces a line feed whenever a carriage return signal is either transmitted or received. Of course, the "C" answer-back code is used.

3. ELECTRICAL INTERFACE BETWEEN TELETYPE AND DATA-PHONE

3.1 TELETYPE SIGNALS. The 33ASRTC Teletype that Northern Scientific supplies as an optional readout device for the NS-550 comes wired by them for three modes of operation: "Tape to Type," "Analyzer Read In," and "Analyzer Read Out." In the first mode, the tape reader supplies data to the printer. In the second mode, the tape reader supplies data only to the memory of the analyzer. The last mode has the printer (and tape punch, if desired) print (punch) out the data in the analyzer's memory. In all these modes, the data is transferred in parallel to and from the analyzer. The parallel-to-serial conversion of the code for each symbol (required for transmission via the Data-Phone) is accomplished electromechanically by the printer mechanism.

The Teletype itself has provision for both "local" and "line" operation. In local mode, an internal power supply provides the 60 ma. loop current required to operate the selector magnet system. Whenever the machine is being used for purposes not requiring a connection to the computer, it should be operated in local mode. In line mode, an external power supply is required, and it is connected to terminals 6 and 7 of terminal strip X. (For details of the Teletype wiring, see reference (4). If the current from the external supply is modulated on and off by the ASCII code for a letter, the machine will print the letter (and punch it as well, if desired). Alternatively, if a key on the keyboard is deppressed, the Teletype itself modulates the line current with the ASCII code. This also happens when a symbol is

Fig. 2: Schematic diagram of the electrical interface



BR_1 : Bridge rectifier assembly (Motorola MDA 942-6)

D_1 : Any small germanium diode

F_1 : $\frac{1}{4}$ amp. slow-blow fuse

S_1 : SPST toggle

T_1 : Isolation transformer, 15 VA. (Triad N-48X)

T_2 : Triad F-90X with taps chosen for ±10 volts d.c. output from supply

Q_1: Silicon NPN, V_{ceo} 150 volts, h_{fe} 30 at I_c 60 ma. (2N5551)

Q_2, Q_3: Silicon NPN, V_{ceo} 25 volts, h_{fe} 10 (2N4124)

Q_4: Silicon PNP, V_{ceo} 25 volts, h_{fe} 10 (2N4126)

printed during operation in "Tape to Type" or in "Analyzer Read Out" mode.

3.2 DATA-PHONE SIGNALS. The Data-Phone transmits and receives all data serially, in the form of pulses of (nominally) plus and minus 15 volts. Full details are given in the manufacturer's interface specification (5).

3.3 THE INTERFACE. The interface translates the modulated line current from the Teletype to positive and negative voltages for the Data-Phone, and vice versa. Fig. 2 is a schematic diagram of the unit. The interface consists of a 60 ma. loop supply, a ±10 volt supply, and two transistorized switches. The incoming signal appears at terminal 3 of the "customer's equipment" connector. Whenever the "Mark" (negative) signal is received, the loop current is switched on by Q1. The "Space" (positive) signal causes Q1 to switch off. The germanium diode connected to the base of Q2 serves two purposes. First, its back resistance is sufficient to assure that Q2 is cut off whenever the Data-Phone is disconnected. Second, it prevents damage to the base-to-emitter junction in the event the Data-Phone produces a negative voltage greater than -10 at terminal 3. (It may go as high as -25, according to the interface specification.)

Q3 and Q4 supply the outgoing signal. The voltage divided connected to the bases of Q3 and Q4 is chosen so that when the Teletype is marking (terminals 6 and 7 of strip X shorted) a negative voltage

at low impedance is presented at pin 2, and when the Teletype is spacing, a corresponding positive voltage at low impedance appears at pin 2.

The continuous positive voltage connected to pin 20 enables the Data-Phone to enter and remain in the "Data" mode.

4. PROGRAMMING REQUIREMENTS

4.1 OUTPUT FORMAT FOR THE NS-550. A typical line of output from the NS-550 consists of a line feed (LF), a carriage return (CR), and eight 6-digit numbers, each separated by a single space from the preceeding. If each memory location contains only 5 decades (which is the case for the NS-550 used in these experiments), the first digit of each number is always zero. The analyzer never prints a plus or minus sign. With the modification described in section 2.3 of this report, the Teletype ignores the line feed, but automatically produces one when it receives the carriage return.

The initial CR and LF is interpreted by the computer as a blank card image, and in order to avoid having the first 8 locations of the input array set equal to zero, the program must be written to read the blank image before reading the first 8 data points.

The following program segment will successfully read JMAX points from the signal analyzer:

```
          READ 100
100       FORMAT (1X)
          DO 10 N=1,JMAX, 8
          NA=N+7
10        READ 101, (INDATA(NZ),NZ=N,NA)
101       FORMAT (8(I6,1X))
```

4.2 ALLOCATION OF STORAGE IN THE NS-550. The 1024 memory locations in the analyzer are divided equally among the input channels being used. The first and last locations in each block of memory are always set to zero, except for the first location in the first block, which always contains the number of sweeps made in the experiment. Data is always read out sequentially by memory address number. Data from Channel A appears in the first block of memory, data from Channel B appears in the second block, and so on. A computed GO TO statement with its argument equal to the number of input channels can be used to assign the data received from the analyzer readout to arrays indexed by channel number (See Appendix A).

4.3 INPUTS SUPPLIED BY THE EXPERIMENTER. Because time-sharing allows conversational interaction between the program and the experimenter, the program can ask for the values of various constants and receive the typed responses directly. The following sets of constants are required:

1. The number of input channels used in the experiment
2. The settings of the input attenuators on the analyzer
3. The matrix of coefficients relating the actual forces and moments to the signals appearing at the input of the analyzer[3]
4. If the experiment involved signal averaging, and the readout did not begin with the first address of memory: the number of sweeps made by the analyzer
5. If the program does a Fourier analysis: the number of data points

in a channel which represent one complete shaft revolution, and the number of harmonics to be computed

6. If the program computes a correlation function: the range of the delay time (the argument of the correlation function)

7. If the program crosscorrelates: the values of the second function or an algorithm for computing these values

The Fourier analyzing program in Appendix A has numerous examples of conversational input-output routines.

5. OPERATING INSTRUCTIONS FOR A SIX-DIMENSIONAL ANALYSIS

It is assumed in these instructions that the reader is familiar with Mr. Horton's thesis (2) which describes the overall design of the complete experimental system, the operation of the NS-550, which is covered in the instruction manual (6), and the CTSS procedures, which are covered in the CTSS User's Manual (7).

PROCEDURE

5.1 Push the STOP button on the NS-550.

5.2 Set: DECADE SELECT to 10^5

READ MODE to CRT

ADD-SUB to ADD

MEMORY GROUP to 1/1

TIME BASE to 2 ms./point

NO. OF SWEEPS TO ∞

DELAY TIME to 1 ms.

PRE DELAY, POST DELAY to OFF

ADDRESS SELECT to OFF

VERTICAL OFFSET to OFF

CONVERSION GAIN to AVE

SWEEP MODE to AVE

TRIGGER to RECURRENT

VIEW INPUT-VIEW MEMORY to VIEW MEMORY

INPUT SELECT to EXT

5.3 Push START READOUT. A pattern of some type should appear on the CRT. If nothing appears, carefully adjust the INTENSITY, HORIZONTAL, and VERTICAL controls until something does. Always keep the INTENSITY control set to the minimum level which produces a visible trace or spot on the CRT. This is especially important when only a single spot appears on the CRT.

5.4 Push the ERASE button. The CRT pattern should immediately degenerate to a straight line. Adjust the VERTICAL POSITION control so this line appears at the very bottom edge of the CRT face. Adjust the HORIZONTAL POSITION and HORIZONTAL EXPAND controls so that this line extends slightly less than the width of the CRT face.

5.5 Push STOP. Then push START MEASURE. Let the unit run for about 10 seconds, then push STOP, followed by START READOUT. This casses a small amount of noise to be read into the memory.

5.6 Set the DECADE SELECT to 10^1 and observe that 10 horizontal lines appear on the CRT. Using the VERTICAL EXPAND and VERTICAL POSITION controls, make these 10 lines coincide with 10 of the 11 scribed reticle lines. This completes calibration of the CRT.

5.7 Push STOP. Set DECADE SELECT to 10^5. Set the INPUT ATTENUATORS for all 4 inputs of the NS-550 and all 4 inputs of the NS-305 to 1 volt. Set all 8 of the AC-DC switches to AC.

5.8 Connect the six strain-gauge outputs from the shaft to channels A through F. Connect the synchronizing pulse cable from the shaft to the positive input of Channel H and also to the EXT

TRIGGER connector.

5.9 Start up the propeller and set the shaft r.p.m. to the value that will be used in the experiment. Set the TIME BASE to .4 ms./point if the r.p.m. is above 1200. Set the TIME BASE to .8 ms./point if the speed is between 600 and 1200 r.p.m. Set the TIME BASE of the NS-305 to the same value that is set on the NS-550.

5.10 Set VIEW INPUT to A. Set TRIGGER to +EXT, and push START MEASURE. Adjust the TRIGGER SENSITIVITY for stable triggering of the horizontal sweep, as indicated by a steady pattern on the CRT that does not move left or right. Center the pattern vertically by using the Channel A BASELINE ADJUST. If the pattern goes off the top or bottom of the CRT, set the Channel A INPUT ATTENUATOR to 10 volts. If the pattern is very small, set the Channel A INPUT ATTENUATOR to 0.1 volt.

5.11 Switch VIEW INPUT to B. Using the Channel B BASELINE ADJUST and INPUT ATTENUATOR, position and vertically scale the pattern as before. Repeat for Channels C and D.

5.12 Set the DECADE SELECT to LOG, and VIEW INPUT-VIEW MEMORY to VIEW MEMORY (this permits viewing of the four inputs of the NS-305). Set VIEW INPUT on the NS-305 to E. Using the Channel E INPUT ATTENUATOR and BASELINE ADJUST, position and scale the pattern as before. Repeat for Channel F.

5.13 Set the VIEW INPUT to G. Center the line using the Channel G BASELINE ADJUST.

5.14 Set VIEW INPUT to H. The pattern should be a straight horizontal

line except for a pulse near the right-hand side. With the BASE-LINE adjust for Channel H, position the straight line about 15% up from the bottom. With the INPUT ATTENUATOR, make the pulse height at least two divisions on the reticle.

5.15 Push STOP. Set DECADE SELECT to 10^4. Push START READOUT. Push ERASE. Push STOP. This completes the adjustments.

5.16 To begin the measurement, push START MEASURE. Initially the CRT will show only a horizontal line at zero. As the experiment continues, vertical deflections will appear and grow. Set DECADE SELECT to 10^5. Continue the experiment until the position of any portion of the trace approaches the top of the CRT. Then push STOP. (Alternative: Set the NO. OF SWEEPS control to 800 before pushing START MEASURE. The analyzer will make 800 sweeps and stop automatically.) This completes the measurement phase of the experiment.

5.17 Turn on the electrical interface between the Teletype and the Data-Phone. Turn on the Teletype in "Line" mode. Set the function switch to "ANALYZER READ OUT." Dial up the computer and LOGIN. Then type LOADGO PROP. The program will begin by asking for a number of constants. The following steps give the details.

5.18 "TYPE NUMBER OF INPUT CHANNELS." Format is I1. Type in the number six. (The sync input on Channel H is not counted as an input.)

5.19 "TYPE INPUT ATTENUATOR SETTINGS." Format is 6F7.2 Type in the settings of the six INPUT ATTENUATORS, A through F.

5.20 "TYPE NUMBER OF OUTPUT CHANNELS DESIRED." Format is I1. Type 6.

5.21 "TYPE NUMBER OF HARMONICS DESIRED." Format is I2. The basic period of analysis is one shaft revolution. EXAMPLE: To obtain analysis up through the third harmonic of the blade rate for a 5-bladed propeller, 15 harmonics are required. The maximum number that can be typed in is 50.

5.22 "ENTER THE N-OUT BY N-IN CALIBRATION MATRIX." The response must be the 6 X 6 strain-gauge calibration matrix C_{ki}, where k, the row subscript, is the output channel number, and i, the column subscript, is the input channel number. The dimensions of each entry must be either ft.-lbf./volt or lbf./volt, and the computer will read six successive rows of six numbers each on a 6F7.2 format.

5.23 "TYPE NUMBER OF DATA POINTS TO BE READ." Format is I4. Type in the number 1024.

5.24 "HERE IS HOW I HAVE YOUR SETTINGS-" The computer will read out all the values as it has them, and gives self-explanatory instructions on what to do if there is an error anywhere.

NOTE: In the next two instructions, the program mentions switching to either manual or automatic line feed. If the modifications described in section 2.3 of this report have been made to the Teletype, the line feed instructions should be deleted from the program.

5.25 "I AM READY TO ACCEPT DATA FROM THE SIGNAL AVERAGER." If a paper

tape of the readout is desired, turn on the tape punch and hit the space bar on the keyboard about 10 times to make a leader on the tape, but do not type a carriage return or a line feed. Push STOP on the NS-550. Set the READ MODE to TYPE and push START READOUT. The readout will take about 15 minutes.

5.26 "SWITCH TO AUTOMATIC LINE FEED AND TYPE CARRIAGE RETURN." See the note above. If this instruction and the read statement immediately following it in the program (Appendix A) have not been deleted, simply hit the carriage return to continue.

5.27 "TYPE NUMBER OF DATA POINTS COMPRISING ONE COMPLETE PERIOD." In the event the program was not able to detect the sync pulse in Channel 8, it will make the above request. If this happens, look at the last 16 rows of the printed readout. Observe that the sixteenth row from the bottom begins with 000000. Number these rows 1 through 16 starting with the one beginning with zeroes. Then find the discontinuity in the printed data values. If R is the row and C is the column where the discontinuity appears, the number to type is 8(R-1)+(C-1). The format is I4.

5.28 "READ OUT NUMBER OF PASSES." If the computer receives a zero for the first number read in from the analyzer, it will make the above request. Push STOP on the NS-550. Set MEMORY GROUP to 1/1 and turn the ADDRESS SELECT switch OFF. Set READ MODE to CRT, Push START READOUT and then push STOP. Set READ MODE to TYPE and push START READOUT. After the first number is printed and before the eighth is printed, push STOP, set READ MODE to CRT, and then hit the carriage return.

5.29 The computer will now read out by channel number and harmonic number the amplitude in lbf. or ft.-lbf and the phase in degrees of each harmonic. The zeroth harmonic is the average, and it has no significance in this type of experiment, since the inputs are all a.c. coupled. The channel numbers can be related to a specific force or moment by a brief consideration of the computation implied by the 6 x 6 calibration matrix.

5.30 "THIS COMPLETES THE ANALYSIS. TYPE 1 TO START AGAIN, 0 TO STOP." If a "1" is typed, the program will return to step 5.25.

APPENDIX

APPENDIX A: "PROP," A COMPUTER PROGRAM FOR FOURIER ANALYSIS

The program described in this section embodies the principles outlined in section 4 and is the program used for the 6-dimensional analysis of section 5. The listing begins on page 32. PROP can be divided into 5 parts:

1. TYPED INPUTS: PROP requests values from the experimenter and provides an opportunity to start again if errors have occurred. (Cards 1-37)

2. ANALYZER READOUT: The program reads the analyzer output into the array INDATA, and then assigns the values to appropriate blocks in the array INPUT, according to the rule stated in section 4.2. If 5 or more input channels are being used, the program scans the contents of Channel 8, looking for a discontinuity of at least 20,000 counts. If it finds such a discontinuity, it sets the number of data points representing one complete shaft revolution equal to the location of the discontinuity. If the discontinuity is not found, or if the number of inputs is 4 or less, PROP requests the experimenter to type in the correct value. (Cards 38-87)

3. MATRIX MULTIPLICATION: The program converts strain-gauge signals into forces and moments. (Cards 88-98)

4. FOURIER ANALYSIS: PROP continues by calculating the coefficients for the Fourier sine and cosine series for each force and moment. (Cards 99-116)

5. OUTPUT: The program determines the number of signal analyzer passes (sweeps), calculates the magnitude and phase of each harmonic for each output channel, prints the results, and provides the experimenter the opportunity to read in new data for the next analysis. (Cards 117-152)

The following is a chart of the variables used in the program.

VARIABLE NAME	RANGE OF VALUES	DESCRIPTION
A(K,L)	lbf./100 counts or ft.-lbf./100 counts	Fourier sine coefficient for the Lth harmonic in the Kth output channel
AMP	ft.-lbf. or lbf.	The magnitude of a harmonic
AVE*	ft.-lbf. or lbf.	The average value of the signal in an output channel
B(K,L)	lbf./100 counts or ft.-lbf./100 counts	Fourier cosine coefficient for the Lth harmonic in the Kth output channel
C	2π/RNDPC	Coefficient used in Fourier series calculations
CALIB(K,I)	lbf./volt or ft.-lbf./volt	The k,i entry in the strain-gauge calibration matrix
FULSCA(I)	.025-100. volts per 100 counts	Input attenuator setting of input channel i
I	1-8	Index giving input channel number
IMAX	1-8	Number of input channels being used in the experiment

INDATA(N)	0-99999	The Nth data point read in from the signal analyzer
INPUT(I,J)	0-99999	The Jth data point in input channel i
J, JP, JPO, etc.	1-1022	Index giving data point number
JMAX	1-1024	Number of data points read
K	1-8	Output channel index number
L	1-50	Index of harmonic being calculated
M	1-50	Number of harmonics the program is to calculate for each output channel
NA	8, 16, 24, etc.	Index used in reading INDATA
NDPC	1-1022	Number of data points per channel which represent one complete period of the input signal
NOUTCH	1-8	Number of output channels
NX, NY	0-1	Branching variables
NZ	1-1024	Index used in reading INDATA
OUTPUT(K,J)	lb./100 counts or ft.-lbf./100 counts	The Jth data point in output channel k
PASSES	1.-99999.	The number of sweeps made by the signal analyzer in an experiment
PHASE**	-90. to +270. degrees	The phase of a harmonic in reference to a sine function of the same frequency

RIN	0.-99999.	Real value of INPUT(I,J)
RJ	1.-1022.	Real value of J
SCOS(J)***	-1.0 to 1.0	Stored value of a cosine
SSIN(J)***	-1.0 to 1.0	Stored value of a sine

---

*AVE is printed as the 0th harmonic in the output format.

**PHASE is initially calculated in radians from the arctangent library routine, and then is converted to degrees, taking account of the quadrant.

***SSIN and SCOS are used to avoid repeated computations of the sine and cosine values needed for the Fourier analysis of a given harmonic in different output channels.

```
CARD
      DIMENSION CALIB(8,8), FULSCA(8)
 80   PRINT 202
 202  FORMAT (1X,30HTYPE NUMBER OF INPUT CHANNELS.)
      READ 203, IMAX
 203  FORMAT (I1)
      PRINT 200
 200  FORMAT (1X,31HTYPE INPUT ATTENUATOR SETTINGS.)
      READ 101, (FULSCA(I),I=1,IMAX)
      PRINT 206
 206  FORMAT (1X,39HTYPE NUMBER OF OUTPUT CHANNELS DESIRED.)
      READ 203, NOUTCH
      PRINT 207
 207  FORMAT (1X,44HTYPE NUMBER OF HARMONICS DESIRED. I2 FORMAT.)
      READ 208,M
 208  FORMAT (I2)
      PRINT 100
 100  FORMAT (1X,43HENTER THE N-OUT BY N-IN CALIBRATION MATRIX.)
      DO 1 K=1,NOUTCH
 1    READ 101,(CALIB(K,I),I=1,IMAX)
 101  FORMAT (8F7.2)
      PRINT 104
 104  FORMAT (38HTYPE NUMBER OF DATA POINTS TO BE READ.)
      READ 407,JMAX
      PRINT 102,IMAX,NOUTCH,M,JMAX,(FULSCA(I),I=1,IMAX)
 102  FORMAT (1X,33HHERE IS HOW I HAVE YOUR SETTINGS-,/
     17HINPUTS-,I2,4X,8HOUTPUTS-,I2,4X,10HHARMONICS-,I3,4X,
     212HDATA POINTS-,I5,/12HATTENUATORS-,/8F7.2)
      PRINT 105
 105  FORMAT (5X,21HCALIBRATION MATRIX-    )
```

```
      DO 2 K=1,NOUTCH
2     PRINT 106, (CALIB(K,I),I=1,IMAX)
106   FORMAT (1X,8F7.2)
      PRINT 103
103   FORMAT (1X,39HIF ALL THESE ITEMS ARE CORRECT, TYPE 1.,/
     11X,33HOTHERWISE,0TYPE 0 TO START AGAIN.)
      READ 203,NY
      IF (NY.EQ.0) GO TO 80
4     PRINT 107
107   FORMAT (1X,51HI AM READY TO ACCEPT DATA FROM THE SIGNAL AVERAGER.,
     1/45HSWITCH TO MANUAL LINE FEED AND START READOUT.)
      DIMENSION INPUT(6,1034), OUTPUT(6,1034),INDATA(1025)
      READ 204
204   FORMAT (1X)
      DO 10 N=1,JMAX,8
      NA=N+7
10    READ 205, (INDATA(NZ),NZ=N,NA)
205   FORMAT (8(I6,1X))
      PRINT 209
209   FORMAT (55HSWITCH TO AUTOMATIC LINE FEED AND TYPE CARRIAGE RETURN.
     1)
      READ 204
      GO TO (400,401,402,402,403,403,403,403), IMAX
400   DO 410 J=1,1022
      JP=J+1
410   INPUT(1,J)=INDATA(JP)
      GO TO 404
401   DO 411 J=1,510
      JP1=J+1
      JP2=J+513
```

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```
      INPUT(1,J)=INDATA(JP1)
411   INPUT(2,J)=INDATA(JP2)
      GO TO 404
402   DO 412 J=1,254
      JP1=J+1
      JP2=J+257
      JP3=J+513
      JP4=J+769
      INPUT(1,J)=INDATA(JP1)
      INPUT(2,J)=INDATA(JP2)
      INPUT(3,J)=INDATA(JP3)
412   INPUT(4,J)=INDATA(JP4)
      GO TO 404
403   DO 413 I=1,8
      JP0=(I-1)*128+1
      DO 414 J=1,126
      JP=J+JP0
414   INPUT(I,J)=INDATA(JP)
413   CONTINUE
      DO 415 J=1,126
      NDPC=J+1
      IF (INPUT(8,NDPC).GT.INPUT(8,J)+20000) GO TO 405
415   CONTINUE
404   PRINT 406
406   FORMAT (1X,50HTYPE NUMBER OF DATA POINTS COMPRISING ONE COMPLETE,
     1/21HPERIOD. USE 4 DIGITS.)
      READ 407, NDPC
407   FORMAT (I4)
405   DO 15 K=1,NOUTCH
      DO 16 J=1,NDPC
```

```
16    OUTPUT(K,J)=0.0
15    CONTINUE
      DO 12 K=1,NOUTCH
      DO 13 J=1,NDPC
      DO 14 I=1,IMAX
      RIN=INPUT(I,J)
14    OUTPUT(K,J)=OUTPUT(K,J)+FULSCA(I)*CALIB(K,I)*RIN
13    CONTINUE
12    CONTINUE
      DIMENSION SSIN(1024), SCOS(1024), A(8,50), B(8,50)
      RNDPC=NDPC
      C=2.*3.1415926536/RNDPC
      DO 20 L=1,M
      RL=L
      DO 30 J=1,NDPC
      RJ=J
      SSIN(J)=SIN(C*RJ*RL)
30    SCOS(J)=COS(C*RJ*RL)
      DO 40 K=1,NOUTCH
      A(K,L)=0.0
      B(K,L)=0.0
      DO 50 J=1,NDPC
      A(K,L)=A(K,L)+OUTPUT(K,J)*SSIN(J)
50    B(K,L)=B(K,L)+OUTPUT(K,J)*SCOS(J)
      A(K,L)=2.*A(K,L)/(RNDPC)
40    B(K,L)=2.*B(K,L)/(RNDPC)
20    CONTINUE
23    IF (INDATA(1).NE.0) GO TO 21
      PRINT 22
22    FORMAT (26HREAD OUT NUMBER OF PASSES.)
```

```
      READ 204
      READ 205,INDATA(1)
      GO TO 23
21    PASSES=INDATA(1)
      DO 60 K=1,NOUTCH
      PRINT 302,K
302   FORMAT (///,8HCHANNEL ,I1,//,1X,27HHARMONIC  AMPLITUDE   PHASE)
      AVE=0.0
      DO 65 J=1,NDPC
65    AVE=AVE+OUTPUT(K,J)
      AVE=AVE/(RNDPC*PASSES*100.)
      PRINT 306,AVE
306   FORMAT (5X,1H0,5X,F9.4)
      DO 70 L=1,M
      AMP=SQRT(A(K,L)**2+B(K,L)**2)/(PASSES*100.)
      IF (A(K,L).EQ.0.0) GO TO 150
      PHASE=ATAN(B(K,L)/A(K,L))
      GO TO 69
150   IF (B(K,L).GE.0.0) PHASE=1.5708
      IF (B(K,L).LT.0.0) PHASE=-1.5708
69    PHASE=57.296*PHASE
      IF (A(K,L) .LT. 0.0))PHASE=PHASE+180.
70    PRINT 303,L,AMP,PHASE
60    CONTINUE
303   FORMAT (4X,I2,5X,F9.4,1X,F7.1)
      PRINT 304
304   FORMAT (///62HTHIS COMPLETES THE ANALYSIS. TYPE 1 TO START AGAIN,
     10 TO STOP.)
      READ 305,NX
305   FORMAT (I1)
      IF (NX .EQ.1) GO TO 4
      STOP
      END
```

APPENDIX B: NOTES

1. Representing the low-impedance source as an ideal voltage source, the transfer function for the capacitor coupled input is

$$H(f) = \frac{j2\pi RCf}{1+j2\pi RCf}$$

A straightforward calculation shows that the phase of H(f) is

$$\phi = \tan^{-1}\left(\frac{1}{2\pi RCf}\right)$$

and the magnitude is

$$\left|H(f)\right| = \frac{1}{\sqrt{1+\frac{1}{(2\pi RCf)^2}}}$$

With the shaft r.p.m. set to 960, f is 16 hz, and with RC .01 sec.,

$$2\pi RCf \approx 1., \quad \phi \approx 45^\circ \quad \text{and} \quad \left|H(f)\right| \approx \frac{1}{\sqrt{2}}$$

Increasing the value of RC to 1 second permits reducing the r.p.m. to only 96. Under these conditions, the phase shift is only 5.7 degrees and the magnitude is down by a factor of only .005.

2. Northern Scientific, Inc., 2551 West Beltline, P.O. Box 66, Middleton, Wisconsin, 53562. Phone (608) 836-6511.

3. In the computer program of Appendix A, each entry in the calibration matrix is assumed to be independent of frequency. If dynamic calibration of the shaft shows that this assumption is not valid, the program will have to be rewritten to do a Fourier analysis of the incoming data before doing the conversion of strain-gauge signals to force and moment outputs. Then each harmonic will have to be converted separately in the program, using values for the calibration matrix entries that are appropriate for the frequency of the harmonic.

APPENDIX C: LIST OF REFERENCES

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